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Potassium and Magnesium Balance the Effect of Nitrogen on the Yield and Quality of Sugar Beet

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Abstract

The yield-enhancing effect of nitrogen (N) in sugar beets depends on the appropriate balance of other nutrients, including potassium (K) and magnesium (Mg). To determine the effects of these nutrients on beet yield (BY), quality parameters, white sugar yield (WSY), and nitrogen use efficiency (NUE) indices, a three-year field study was conducted in western Poland. Eight different fertilization treatments with potassium salt (PS), Korn-Kali (KK), and magnesium sulfate (Mg) were tested, K_0, K_1 (PS), K_2 (PS), K_2 (PS) + Mg, K_1 (KK), K_2 (KK), K_2 (KK) + Mg, K_2 (KK) + Mg + FF, where 0, 1, and 2 are the K rates, respectively, for 0, 83, and 163 kg K ha^{-1}, and FF denotes foliar fertilization with magnesium sulfate. Potassium fertilization, both in the form of PS and KK, along with additional application of magnesium sulfate, positively affected BY and WSY. However, the response to fertilization depended strongly on seasonal factors, such as weather and soil conditions. Compared to the treatment without potassium (K_0), the average BY increased by 6.5–9.1%, and the WSY by 4.6–9.0%. Mineral fertilization had little effect on taproot quality parameters, including sucrose content. The exception was the concentration of α-amino-N, which significantly decreased with the application of K fertilizers. However, changes in α-amino-N content were not significantly related to WSY levels because this characteristic primarily depended on BY each year, and applying K and Mg to the soil improves NUE indices.

Keywords: foliar fertilization; kieserite; leaf yield; magnesium; nitrogen agronomic efficiency; potassium; sodium; sulfur

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1. Introduction

Sugarcane and sugar beet are the dominant crops used for sugar production. The former, grown in the tropical and subtropical zones, dominates, providing ¾ of sugar production [1]. The latter is grown in temperate regions of the world. The main reason for the difference in yield for sugar beet is weather conditions; in particular, summer months are crucial for good yields [2]. Approximately 150 mm of precipitation is required in July and August to optimize the yield potential of sugar beets in the Northern Hemisphere [3]. These conditions allow plants to undergo non-limiting growth in the mead season, which is critical for optimizing their yielding potential [4,5]. In Central Europe, including Poland, such weather conditions are the exception rather than the rule [6,7].

One of the basic mistakes made by sugar beet producers is the assumption that sugar beet requires large nitrogen fertilizer (N_f) rates. This assumption results from the incorrect assumptions of a number of field experiments previously conducted testing extremely large rates of N_f [7]. Sugar beet, as the latest research shows, requires moderate N rates. It

is designed to ensure intensive plant growth in the period until (i) the rows are covered and (ii) the maximum assimilation area is achieved [8]. In the Northern Hemisphere, the maximum intensity of solar energy occurs at the end of June. Its effective use by sugar beet depends on the rate of canopy leaf growth [9]. Key indicators of the plant's nutritional status at early stages of sugar beet growth are both the nitrogen (N) and potassium (K) content in fully developed leaves, as well as their ratio. Assuming a critical N content of 4%, the required K content should exceed 5% [7,10]. The maximum growth of both leaves and taproots in Poland occurs at the end of July, and the required ratio between the amount of accumulated N and K is 1:1.5 (2) [11]. With optimal nutritional conditions for sugar beet plants, taproot yield (BY) can reach 90 t ha^{-1}, and white sugar yield (WSY) can reach 14 t ha^{-1} [12]. However, in Poland, actual beet yields in the period 2021–2024 were much lower and amounted to 62 ha^{-1} and 9 ha^{-1}, respectively [13]. The potential yield gap, as shown by field studies, is about 33%. One important cause of the yield gap is insufficient natural soil fertility related to K content and main cations, such as calcium (Ca) and magnesium (Mg) cations [14].

During the entire vegetation period of sugar beet, K is mainly responsible for (i) N uptake and utilization, (ii) water management control, and (iii) sucrose transport from leaves to the storage root. It is well documented that higher amounts of plant-available K in the soil result in faster sugar beet root growth, thereby resulting in deeper plant rooting [15]. Potassium plays a fundamental role in the uptake of N by plants, more precisely nitrate nitrogen (NO_3-N) [16,17]. The dynamics of NO_3-N uptake are several times higher than those of K^+ ions. This leads to a phenomenon called "ion depletion", which is due to the high natural mobility of NO_3-N in the soil [18]. The depletion zone is revealed in the entire rooting layer of the plant, but the greatest depletion occurs in the soil layer up to 50–60 cm. The depletion zone develops much faster in naturally poor or mined soil with plant-available K [11]. A decrease in the NO_3-N concentration in the soil solution triggers a plant response leading to increased root growth. Under K deficiency, growth dynamics are inhibited and the root system is reduced [19,20]. A significant factor disturbing the growth and yield of crops is the excessive exploitation of K resources in the soil, a phenomenon known as soil mining. On a global scale, this factor significantly threatens agricultural production [21,22]. In Central Europe, such processes occurred in the 1990s, and the effects are still felt today [23]. Deficiency in plant-available K in the soil results not only in slower plant growth but also in an increased response to water deficiency [24]. Figure 1 shows the condition of sugar beet plantations (above-ground mass) during a drought in soil that has not been fertilized with potassium for several years in crop rotation.

Soils in Poland that are used to grow sugar beets are highly sensitive to the current K supply because they are typically Luvisols. These soils formed from sandy loam or loamy sand [25]. Therefore, soil for sugar beet cultivation must be prepared such that the plant has a suitably large excess of available K in the top layer of the subsoil, which causes NO_3^- ions to be quickly taken up [26]. The current fertility of these soils depends on three main farming activities: (i) soil pH control through limiting, (ii) soil organic matter control through manure application, and (iii) maintaining a continuous external supply of fertilizers containing phosphorus (P), K, magnesium (Mg), etc. The entire process of K fertility gap amelioration requires a well-developed farming strategy based on effective K management through crop rotation [14,16,20]. This applies not only to the selection of the appropriate rate and timing of K application but also the correction of the content of other nutrients in the soil, particularly cations, or in other words, the appropriate K balance [27]. Along with P and K, Mg and sulfur (S) are key nutrients that determine the dynamics of plant growth, taproot development, and white sugar yield. Sugar beet requires much less Mg and S than K [14]. However, Mg plays a vital role in various physiological

and biochemical processes. It is crucial for chlorophyll synthesis, photosynthesis, enzyme activation, and carbohydrate distribution [28]. Mg deficiency not only negatively affects yield levels but also reduces the technological quality of sugar beet taproots [29,30]. The primary function of S is to regulate the processes that convert absorbed N into leaf mass. This process is crucial for beet growth in June and July. Consequently, the growth dynamics of the taproot increase, as does the taproot's dry matter [31]. Plants well nourished with S contain less alpha-amino N (α-N) in the taproot, which results in a higher production of "white" sugar [32,33]. However, the application of fertilizer S reveals poor S availability in soils when the precipitation is much lower than that required by the crops [34].



Figure 1. Sugar beets—slow growth, poorly formed leaves, and susceptibility to water deficiency, the effects of several years K mining. Author: Witold Grzebisz.

This study investigated the following research hypothesis: sugar beet plants, under balanced fertilization with K and macronutrients and secondary components, effectively use nitrogen, thus maximizing their production potential. The research objective formulated on this basis assumed that balanced fertilization of sugar beet with K, Mg, and S would increase the productivity of fertilizer N and thus the white sugar yield.

2. Materials and Methods

2.1. Experimental Site

A three-year (2016, 2017 and 2018) field study with sugar beets (*Beta vulgaris* L.) was carried out on a farm in Bodzewo, in central-west Poland (Figure 2).

The field experiment was conducted on Albic Luvisol (Neocambic) formed from loamy sand underlined with light loam [25]. Over the years of the study, the soil differed in both texture and organic carbon (C-org) content. In 2016, the contents of sand, silt, and clay in the 0–30 cm soil layer were 74, 19, and 7%, respectively. In 2017, the shares of these soil particles were 71, 17, and 12%, and in 2018, they were 73, 16, and 11%, respectively. Hence, the soil in 2017–2018 was classified as the sandy loam group, and as loamy sand only in the first year (2016). The C-org content in the 0–30 cm soil layer was 12.5, 10.1, and 9.4 g kg^{-1}, respectively, for 2016, 2017 and 2018. In the first two years, soil pH was neutral throughout the soil profile. In the third season, it was slightly acidic, increasing with soil depth. Plant-available P was very high in the topsoil, falling drastically to a very low class

in the subsoils. This trend is typical for Luvisols [35]. Plant-available K content varied between years and between soil layers in a given season. In 2016 and 2017, it was in the low class. In 2016, it was low but constant with soil depth. In 2017, its content in topsoil was much higher compared to 2016 and decreased in the subsoil. In 2018, it remained stable in the medium class throughout the entire soil profile. The content of plant-available Mg was classified as high in all growing seasons. However, in 2016, its content was significantly lower than in the following years. Calcium content varied over the years, and also between layers in a given growing season. In 2016, it was low in topsoil, increasing to very high in subsoil. In 2017, it was constant throughout the soil profile, classified as medium. In 2018, the class and depth trend were analogous to those in 2016, but the values were lower. The amount of mineral N (N_{min}), measured just before sugar beet sowing in the 0–90 cm m soil layer, was generally high and ranged from 100 kg ha^{-1} in 2016 to 113 kg ha^{-1} in the remaining seasons. The dominant form was nitrate nitrogen (NO_3-N), which accounted for 75% to 90% of the total N_{min} (Table 1).

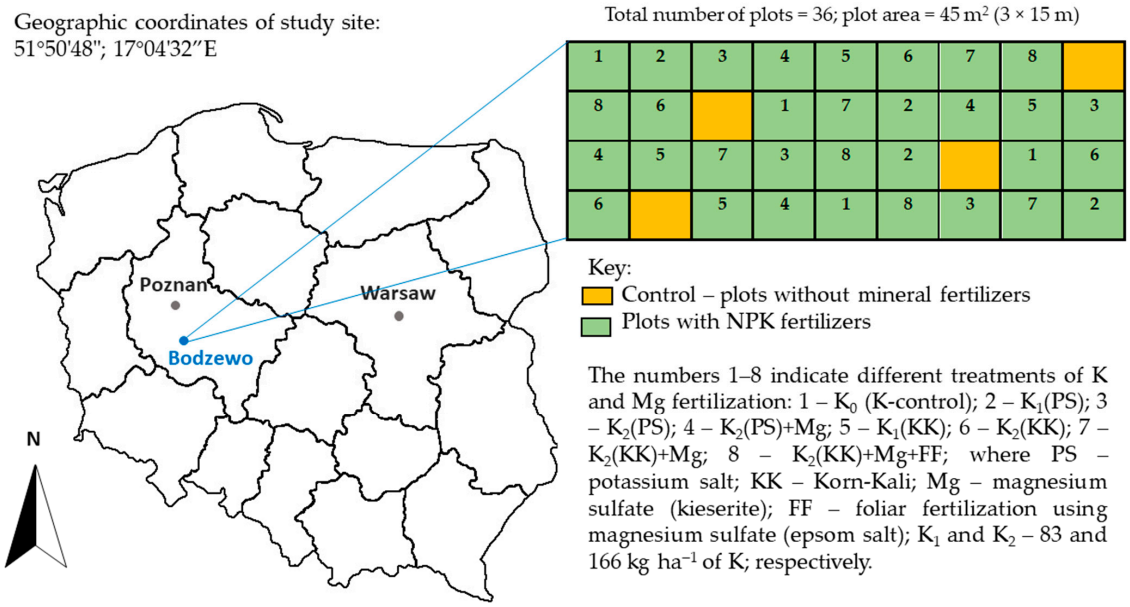

Figure 2. Location of the field experiment with sugar beet in central-west Poland.

Table 1. Agrochemical characteristics of soil before applying fertilizers and sugar beet sowing.

Year	Soil Depth, cm	pH [1]	P [2]	K [2]	Mg [2]	Ca [2]	NH_4-N [3]	NO_3-N [3]	NH_4-N + NO_3-N
			mg kg^{-1}				kg ha^{-1}		
2016	0–30	7.2	73.1 M	82.5 L	109 VH	1230 L	5.0	12.0	17.0
	30–60	7.1	5.4 VL	82.2 L	213 VH	7676 VH	5.2	21.5	26.7
	60–90	7.0	5.3 VL	83.2 L	234 VH	10,778 VH	5.0	51.4	56.4
	Total						15.2	84. 9	100.1
2017	0–30	6.6	127 M	127 L	195 VH	2290 M	8.1	21.0	29.1
	30–60	6.9	17 VL	117 L	294 VH	2300 M	9.1	20.4	29.5
	60–90	7.1	7 VL	92 VL	310 VH	2240 M	12.0	42.9	54.9
	Total						29.2	84.3	113.5
2018	0–30	6.0	105 M	183 M	177 VH	1151 L	2.9	23.5	26.4
	30–60	6.4	21.1 VL	145 M	254 VH	6534 H	4.6	30.0	34.6
	60–90	6.7	8.3 VL	149 M	326 VH	7674 VH	4.1	47.9	52.0
	Total						11.6	101.4	113.0

[1] The 1.0 mol L^{-1} soil/solution ratio, 1:2.5 *m*/*v*; [2] Mehlich 3 method [36]; availability classes: VL—very low; L—low; M—medium; H—high; VH—very high [37,38]; [3] soil depth, 0–90 cm, measured in 0.01 M $CaCl_2$.

2.2. Weather Conditions

The local climate in the geographical area of the field experiment is classified as moderate climatic zone (transitional between Atlantic and Continental). In the summer months, continental conditions dominate, with high temperatures, thunderstorms, and locally distributed rains. The climate of the study area in the period 1964–2015 was characterized by an average annual temperature of 8.1 °C (in the range from 6.6 to 10 °C) and total precipitation of about 580 mm per year (in the range from 310 to 840 mm). During the study years (2016–2018), average monthly temperatures were higher than the long-term averages (Figure 3). Consequently, the average annual temperatures were higher, amounting to 9.5, 9.8, and 11.0 °C for 2016, 2017, and 2018, respectively. In general, the observed temperatures promoted the growth of sugar beet plants, enabling faster row coverage and more efficient use of soil water. The second environmental parameter, i.e., atmospheric precipitation, as well as its sum and distribution during the growing season, differed significantly between the years of this study. The total precipitation in 2016, 2017, and 2018 was 704, 569, and 464 mm, respectively. The total precipitation during the growing seasons in the following years was 445, 406, and 312, respectively. However, sugar beet yield was determined by the specific course of weather conditions in individual months, related to both temperature and precipitation, and not only the total precipitation during the growing season. The Discussion Section provides a detailed analysis of the relationship between weather conditions and the yield and quality of sugar beet taproots.

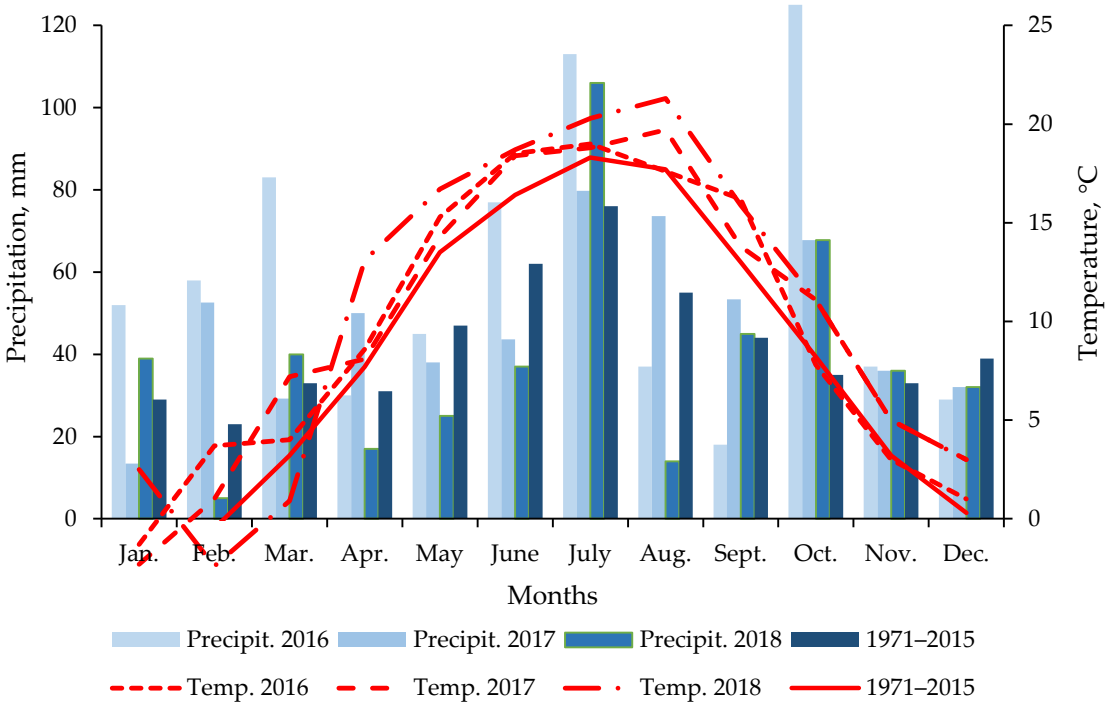

Figure 3. The course of weather conditions in the 2016–2018 growing seasons against the background of long-term data (1964–2015).

2.3. Experimental Design

The data used in this study came from a one-factor field experiment. The experiment was replicated four times. Eight different treatments of K fertilization were tested, including two rates (K_1, K_2) and two types of K fertilizer. Details of the experimental design (fertilization treatments) are shown in Table 2. Potassium was applied in accordance with the experimental schedule in two forms: (i) PS—potassium salt (KCl, 60% K_2O, producer: K + S, Kassel, Germany); (ii) KK—Korn-Kali (40-6-3-12.5% of K-MgO-Na_2O-SO_3, producer:

K + S, Kassel, Germany). In 3 treatments, Mg and S were also introduced into the soil in the form of magnesium sulfate—ESTA Kieserite ($MgSO_4 \times H_2O$; 25% MgO, 50% SO_3, producer: K + S, Kassel, Germany). Phosphorus was applied in the form of triple superphosphate (46% P_2O_5). All these fertilizers were applied to the soil just after forecrop harvest (in autumn). One of the treatments included foliar fertilization using magnesium sulfate—EPSO Top ($MgSO_4 \times 7H_2O$; 16% MgO, 32% SO_3, producer: K + S, Kassel, Germany). Table 3 provides details on spray rates and timing. Nitrogen fertilization in the form of ammonium nitrate (NH_4NO_3; 34% N) was carried out two weeks before sowing the plants. Additionally, an absolute control—treatment without any fertilizer—was prepared. In this study, it was only used to calculate indices of nitrogen use efficiency (NUE). The area of a single plot was 45 m^2 (3 × 15 m). Sugar beet cv. Gellert was sown annually after winter wheat as forecrop in the first week of April at 100,000 seeds per m^2. Plants were protected in accordance with the principles of the Code of Good Practice.

Table 2. Experimental treatments—rates of macronutrients in the experiment, kg ha^{-1}.

Treatment (Acronym)	Macronutrients and Sodium					
	N	P	K	Mg	S	Na
K_0	110	26	0	0	0	0
K_1 (PS)	110	26	83	0	0	0
K_2 (PS)	110	26	166	0	0	0
K_2 (PS) + Mg	110	26	166	48	67	0
K_1 (KK)	110	26	83	9	12.5	7.4
K_2 (KK)	110	26	166	18	25	14.8
K_2 (KK) + Mg	110	26	166	18 + 30	25 + 42	14.8
K_2 (KK) + Mg + FF	110	26	166	18 + 30 + 4.1	25 + 42 + 5.6	14.8

PS—potassium salt; KK—Korn-Kali; Mg—magnesium sulfate (kieserite); FF—foliar fertilization using magnesium sulfate.

Table 3. Timing of magnesium sulfate ($MgSO_4 \times 7H_2O$) application to sugar beet foliage.

Application Timing	Maximum Concentration	Rate kg ha^{-1}	BBCH Code	Description
1st	5%	15	15	Five-leaf stage
2nd	(20 kg in 400 dm^3 of	15	38	Before closing of rows
3rd	water per ha)	15	45	End of July

2.4. Harvest and Analysis of Crop Quality

The crop was harvested at the end of October from an area of 27 m^2 (2.7 × 10 m). The storage roots (taproots) were separated from the aboveground biomass, i.e., tops. Both plant parts were then weighed. To assess beet quality, 20 taproots were randomly selected from each plot. The taproots were analyzed at the Środa Wielkopolska sugar factory (Pfeifer & Langen company, Poznań, Poland) using a Venema auto-analyzer IIIG (Venema Consulting, Groningen, The Netherlands). The taproots were washed, and then the brei was prepared and clarified with a 0.3% aluminum sulfate solution (in a ratio of 1:6.846; *w*/*w*). K and Na concentrations were determined via flame photometry (at wavelengths of 766.5 and 589.0, respectively), and α-amino N was analyzed using copper nitrate solution. The color intensity of copper complexes with free nitrogen compounds in solution was measured at 610 nm. The sucrose concentration (SC) was determined using polarimetry. Standard molasses loss (SML), white sugar content (WSC), and white sugar yield (WSY) were calculated according to the standard method as follows [39]:

$$SML = 0.12\ (K + Na) + 0.24\ \alpha\text{-}N + 0.48 \quad (1)$$

$$WSC = SC - SML - SFL \quad (2)$$

$$WSR = (WSC \times 100)/SC \quad (3)$$

$$WSY = (BY \times WSC)/100 \quad (4)$$

where SML—standard molasses loss (%); K + Na—sum of potassium and sodium concentration in taproots (mM 100 g^{-1}); α-N—α-amino-N concentration in taproots (mM 100 g^{-1}); WSC—white (technological) sugar content (%); SC—sucrose concentration, polarization (%); SFL = standard factory loss (0.6%); WSR—white sugar recovery (%); and BY—taproot yield (t ha^{-1}).

2.5. Nitrogen Use Efficiency Indices

In order to assess the nitrogen use efficiency (NUE) in the soil–plant system, the following indices were used [40]:

$$\text{Partial Factor Productivity of } N_f \ (PFP_f) = BY/N_f \ [\text{kg BY kg}^{-1} \ N_f] \quad (5)$$

$$\text{Agronomic efficiency of } N_f \ (AE) = (BY - TY_0)/N_f \ [\text{kg BY kg}^{-1} \ N_f] \quad (6)$$

$$\text{Biomass productivity of } N_{in} \ (NUE_s) = (BY + LY)/(N_{min} + N_f) \ [\text{kg kg}^{-1} \ N_{in}] \quad (7)$$

$$\text{Partial factor productivity of } N_{in} \ (PFP_{in}) = BY/(N_{min} + N_f) \ [\text{kg BY kg}^{-1} \ N_{in}] \quad (8)$$

where BY—sugar beet taproot yield, kg ha^{-1}; BY_0—sugar beet taproot yield in treatment without N fertilizers, kg ha^{-1}); N_f—total N input in fertilizers, kg N ha^{-1}; LY—leaf yield at harvest, kg ha^{-1}; and N_{in}—total N input from the soil in the spring (N_{min}, 0.0–0.90 m) and mineral fertilizers (N_f), kg N ha^{-1}.

2.6. Statistical Analysis

The effect of fertilization on sugar beet yield, quality parameters, and NUE indices was evaluated using one-way ANOVA (separately for each year) and two-way ANOVA in order to assess interactions between two factors: year and K-treatment. Means were separated by the honest significant difference (HSD) using Tukey's method, when the F-test indicated a significant effect at a level of $p \leq 0.05$. The distribution of the data (normality) was checked using the Shapiro–Wilk test. The homogeneity of variance was checked using Bartlett's test. Correlation and stepwise multiple regression were used to assess the relationships between features. Statistica 13 software was used for all statistical analyses (TIBCO Software Inc., Santa Clara, CA, USA).

3. Results

3.1. BEET Yield

Sugar beet yield (BY) was significantly influenced by the interaction between two factors: the growing season and K fertilization treatments. However, the seasonal factor was clearly dominant in shaping BY (Table S1). The highest BY was obtained in 2018. This yield was 16.8% and 12.6% higher than in 2016 and 2017, respectively (Table 4).

A significant increase in BY was observed in the K fertilization treatments in comparison to the control treatment without K. The only exception was the treatment with the highest rate of potassium salt [K_2 (SP)]. The highest average BY was obtained with the K_2 (KK) + Mg treatment (+9.1% compared to the K_0 treatment). At the same time, the differences between K_2 (KK) + Mg and other treatments were small and insignificant. However, the difference in BY between K_2 (KK) + Mg and K_1 (SP) was 5.4% (Table 5).

Table 4. Effect of growing season on sugar beet taproot yield (BY), leaf yield (LY) and BY/LY ratio.

Year	Beet Yield (BY) t ha^{-1}	Leaf Yield (LY) t ha^{-1}	BY/LY Ratio
2016	71.0 ± 0.81 ^{c}	41.0 ± 0.81 ^{a}	0.59 ± 0.01 ^{a}
2017	73.6 ± 0.52 ^{b}	34.1 ± 0.81 ^{b}	0.46 ± 0.01 ^{b}
2018	82.9 ± 0.71 ^{a}	35.7 ± 1.06 ^{b}	0.43 ± 0.01 ^{b}
F ratio	127.4 ***	15.6 ***	44.9 ***

*** *F*-ratio significant at $p \leq 0.001$. Different letters indicate significant differences between treatments (Tukey's HSD test; $p \leq 0.05$).

Table 5. Sugar beet taproot yield (BY, t ha^{-1}) in relation to the growing season and K fertilization treatment (mean ± SEM).

Treatment	Year			Mean
	2016	2017	2018	
K_0	66.8 ± 2.13	69.6 ± 0.48 ^{c}	77.5 ± 2.17 ^{c}	71.3 ± 1.65 ^{b}
K_1 (SP)	71.5 ± 1.88	76.6 ± 1.12 ^{ab}	83.7 ± 0.99 ^{abc}	77.3 ± 1.67 ^{a}
K_2 (SP)	69.9 ± 2.08	72.4 ± 0.32 ^{abc}	79.2 ± 1.26 ^{bc}	73.8 ± 1.40 ^{ab}
K_2 (SP) + Mg	73.7 ± 2.15	75.1 ± 1.06 ^{ab}	83.4 ± 2.00 ^{abc}	77.4 ± 1.60 ^{a}
K_1 (KK)	68.3 ± 0.60	76.9 ± 0.58 ^{a}	85.9 ± 1.38 ^{ab}	77.1 ± 2.22 ^{a}
K_2 (KK)	69.3 ± 2.10	72.1 ± 1.65 ^{bc}	86.7 ± 1.42 ^{a}	76.0 ± 2.46 ^{a}
K_2 (KK) + Mg	75.9 ± 2.89	72.6 ± 1.36 ^{abc}	84.9 ± 1.06 ^{ab}	77.8 ± 1.86 ^{a}
K_2 (KK) + Mg + FF	72.4 ± 2.00	73.2 ± 0.65 ^{abc}	81.7 ± 0.79 ^{abc}	75.8 ± 1.43 ^{a}
F ratio	2.09 $^{n.s.}$	6.11 ***	4.90 **	6.00 ***

, * *F*-ratio significance at $p \leq 0.01$, 0.001, respectively; n.s., not significant. Different letters indicate significant differences between treatments (Tukey's HSD test; $p \leq 0.05$).

The effect of fertilization treatments on BY was modified by the seasonal factor. However, in 2016, this factor did not have a significant effect on BY, and a clear trend toward higher yields was observed when K and other nutrients were used. The highest BY was obtained with the K_2 (KK) + Mg treatment, followed by the K_2 (SP) + Mg treatment. Compared to the potassium control (K_0), BY was 13.6% and 10.2% higher, respectively. Applying potassium salt at a higher rate [K_2 (SP)] slightly reduced BY compared to the [K_1 (SP)] treatment. The additional application of foliar fertilizer did not increase the yield level. In 2017, a significant effect of fertilization was observed. BY values in the K_1 (KK), K_2 (SP) + Mg, and K_1 (SP) treatments were significantly higher than in the K_0 treatment, with differences ranging from 7.9% to 10.5%. In the other treatments [K_2 (SP), K_2 (KK), K_2 (KK) + Mg and K_2 (KK) + Mg + FF], higher BY was also obtained compared to the K_0 treatment. However, the differences were lower (3.6–5.2%) and not statistically significant (the same homogeneous group). In 2018, the highest BY values were obtained in the K_1 (KK), K_2 (KK), and K_2 (KK) + Mg treatments. BY increased by 9.5% and 11.8%, respectively, compared to the K_0 treatment. Applying the highest rate of KCl alone or with magnesium sulfate, as well as additional foliar fertilization, did not significantly increase BY (Table 5).

3.2. Leaf Yield

Unlike BY, leaf yield (LY) depended significantly only on the growing season (Table S1). Furthermore, the highest LY was recorded in 2016, not 2018. This value was 20.0% and 14.9% higher than in 2017 and 2018, respectively. Consequently, the highest BY/LY ratio was recorded in 2016, while the lowest ratio was recorded in 2018 (Table 4).

Fertilization did not significantly affect LY in any of the individual years of the study or in the three-year average (Tables 6 and S1). Furthermore, the differences between treatments in individual years were inconsistent and unclear. On average, the highest LY values were obtained with the following treatments: K_1 (KK) and K_2 (KK) + Mg + FF. At the same time,

a trend of decreasing leaf biomass with an increasing K rate and additional Mg applications was noted, regardless of the K fertilizer. The K_2 (KK) + Mg + FF treatment was the only one to not follow this pattern because foliar fertilization had a positive effect on LY (Table 6).

Table 6. Sugar beet leaf yield (LY, t ha^{-1}) in relation to the growing season and K fertilization treatment (mean ± SEM).

Treatment	Year			Mean
	2016	2017	2018	
K_0	43.3 ± 2.69	34.6 ± 2.85	32.0 ± 0.78	36.6 ± 1.89
K_1 (SP)	43.8 ± 2.15	34.0 ± 2.54	34.9 ± 1.63	37.6 ± 1.74
K_2 (SP)	38.1 ± 2.42	35.1 ± 1.44	35.7 ± 0.41	36.3 ± 0.95
K_2 (SP) + Mg	38.0 ± 1.49	31.1 ± 1.54	33.9 ± 1.62	34.3 ± 1.18
K_1 (KK)	42.4 ± 1.69	37.0 ± 2.76	36.8 ± 2.05	38.7 ± 1.41
K_2 (KK)	39.6 ± 1.36	33.8 ± 2.52	39.6 ± 5.97	37.7 ± 2.16
K_2 (KK) + Mg	41.1 ± 1.37	31.1 ± 1.68	32.8 ± 1.20	35.0 ± 1.51
K_2 (KK) + Mg + FF	41.4 ± 3.99	36.4 ± 2.74	39.8 ± 5.04	39.2 ± 2.20
F ratio	0.93 $^{n.s.}$	0.87 $^{n.s.}$	0.92 $^{n.s.}$	1.31 $^{n.s.}$

n.s., no significant *F*-ratio.

In contrast to LY, the average BY/LY ratios were significantly impacted by fertilization (Table S1). However, a significant difference was noted only between the K_0 and K_2 (SP) + Mg treatments, but not between any other pairs of BY/LY ratios (Table S2). No significant effect of fertilization on the BY/LY ratio was found in the individual growing seasons.

3.3. Beet Quality and White Sugar Yield

The seasonal factor significantly affected the quality of the taproots. The highest sucrose concentration was found in 2018, when the taproots of sugar beets also contained the highest concentration of molasses-forming compounds. Consequently, the highest potential losses of sugar to molasses (SML) and the lowest sugar recovery in the technological process (WSR) were observed this year. Taproots harvested in 2017 had the lowest SC. These taproots also had the lowest α-N concentration. This resulted in the lowest SML values this year. However, 2016 had a higher sugar recovery efficiency (Table 7).

Table 7. The quality parameters of sugar beet taproots in relation to the growing season and K fertilization treatment (mean ± SEM).

Year/Treatment	SC %	α-N	K mmol kg^{-1}	Na	SML %	WSC %	WSR %
2016	18.75 ± 0.07 ^{b}	23.4 ± 0.79 ^{b}	30.1 ± 0.44 ^{b}	2.79 ± 0.08 ^{c}	2.04 ± 0.02 ^{b}	16.71 ± 0.07 ^{b}	89.1 ± 0.13 ^{a}
2017	16.81 ± 0.05 ^{c}	15.4 ± 0.28 ^{c}	31.3 ± 0.37 ^{b}	3.80 ± 0.08 ^{b}	1.87 ± 0.01 ^{c}	14.94 ± 0.05 ^{c}	88.9 ± 0.07 ^{ab}
2018	20.80 ± 0.12 ^{a}	31.5 ± 0.87 ^{a}	39.0 ± 0.64 ^{a}	5.14 ± 0.12 ^{a}	2.37 ± 0.02 ^{a}	18.44 ± 0.14 ^{a}	88.6 ± 0.17 ^{b}
K_0	18.83 ± 0.51	26.5 ± 2.5 ^{a}	33.2 ± 1.3	3.73 ± 0.33	2.16 ± 0.07	16.67 ± 0.46	88.5 ± 0.22
K_1 (SP)	18.68 ± 0.54	23.5 ± 2.3 ^{ab}	33.8 ± 1.2	4.07 ± 0.32	2.10 ± 0.07	16.58 ± 0.49	88.8 ± 0.19
K_2 (SP)	18.92 ± 0.56	22.8 ± 2.5 ^{ab}	33.5 ± 1.5	3.64 ± 0.26	2.07 ± 0.08	16.85 ± 0.49	89.1 ± 0.19
K_2 (SP) + Mg	18.78 ± 0.51	23.6 ± 2.4 ^{ab}	34.7 ± 1.9	3.84 ± 0.30	2.11 ± 0.08	16.67 ± 0.45	88.8 ± 0.28
K_1 (KK)	18.80 ± 0.48	22.4 ± 1.9 ^{ab}	32.5 ± 1.3	4.01 ± 0.38	2.06 ± 0.06	16.74 ± 0.43	89.1 ± 0.16
K_2 (KK)	18.73 ± 0.49	23.6 ± 2.3 ^{ab}	34.0 ± 1.6	3.93 ± 0.27	2.10 ± 0.07	16.62 ± 0.45	88.8 ± 0.30
K_2 (KK) + Mg	18.73 ± 0.49	23.7 ± 2.2 ^{ab}	33.4 ± 1.5	3.97 ± 0.31	2.10 ± 0.07	16.63 ± 0.43	88.8 ± 0.19
K_2 (KK) + Mg + FF	18.84 ± 0.51	21.3 ± 1.8 ^{b}	32.6 ± 3.0	4.08 ± 0.44	2.03 ± 0.06	16.80 ± 0.43	89.2 ± 0.19
			ANOVA (*F ratio*)				
Year (Y)	486.6 ***	165.8 ***	87.5 ***	150.1 ***	203.4 ***	292.4 ***	4.0 *
Treatment (T)	0.30 $^{n.s.}$	2.14 *	0.76 $^{n.s.}$	1.02 $^{n.s.}$	1.78 $^{n.s.}$	0.94 $^{n.s.}$	1.0 $^{n.s.}$
Interaction Y × T	0.51 $^{n.s.}$	2.06 *	0.69 $^{n.s.}$	1.11 $^{n.s.}$	1.80 $^{n.s.}$	0.93 $^{n.s.}$	1.0 $^{n.s.}$

*, *** F-ratio significant at $p \leq 0.05$, 0.001, respectively; n.s., not significant. Different letters indicate statistically significant differences between treatments (Tukey's HSD test; $p \leq 0.05$). Key: SC—polarization, biological sucrose content; α-N—α-amino-N concentration; K and Na—potassium and sodium concentration; SML—standard molasses loss; WSC—white (technological) sugar content; WSR—white sugar recovery.

The effect of the fertilization factor was not significant for most of the studied quality parameters compared to the seasonal factor. Only the average α-N concentration showed

significant differences as a result of K fertilization. Furthermore, the α-N concentration depended on the "season × fertilization" interaction (Table 7). A significant effect of the fertilization factor on this feature was observed in 2016 (Table S3). In 2017, a clear trend toward lower α-N concentrations was also observed in the taproots of plants fertilized with potassium (K). As a result, the taproots of plants collected from the K_0 treatment had a significantly higher α-N concentration than the taproots from the other treatments, except for the K_2 (KK) treatment (Table 7).

Foliar fertilization improved the technological quality of the taproots and significantly reduced the α-N concentration compared to the control, independently of the seasonal factor. However, it is worth noting that the other fertilization treatments also positively affected beet quality by reducing the α-N concentration. Consequently, a trend emerged to lower the SML value through the use of K fertilizers and magnesium sulfate (Table 7).

The average WSY values were significantly affected by K fertilization (Table S4). At the same time, a specific response to fertilization was observed in individual years of this study. In the first year, the highest increase in WSY compared to the K_0 treatment was observed in treatments with soil-based fertilization using magnesium sulfate (Figure 4a). In 2017, the highest WSY was achieved with beets fertilized with Korn-Kali at a lower rate [K_1 (KK)]. Nevertheless, WSY in this treatment was significantly higher compared only to K_0 (Figure 4b), with a difference of 1.4%. In 2018, there were no significant differences between the fertilization treatments. However, a trend toward higher WSY in plants fertilized with Korn-Kali but without soil Mg and S application was observed (Figure 4c). Due to the varied effect of fertilization in individual years, the average WSY values for most K-containing treatments did not differ significantly. Only a statistically significant difference was obtained between the control and treatments with K, except for K_2 (PS). The difference in WSY between the K_0 and the other treatments ranged from 6.4% [K_2 (KK)] to 9.0% [K_2 (KK) + Mg] (Figure 4d).

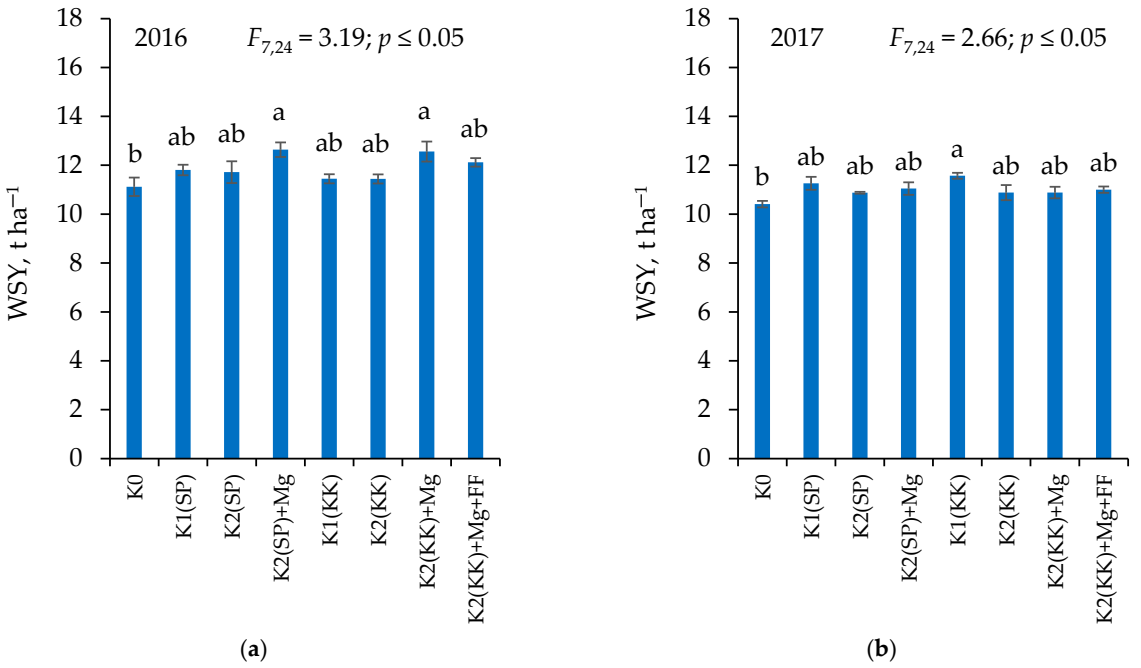

Figure 4. *Cont.*

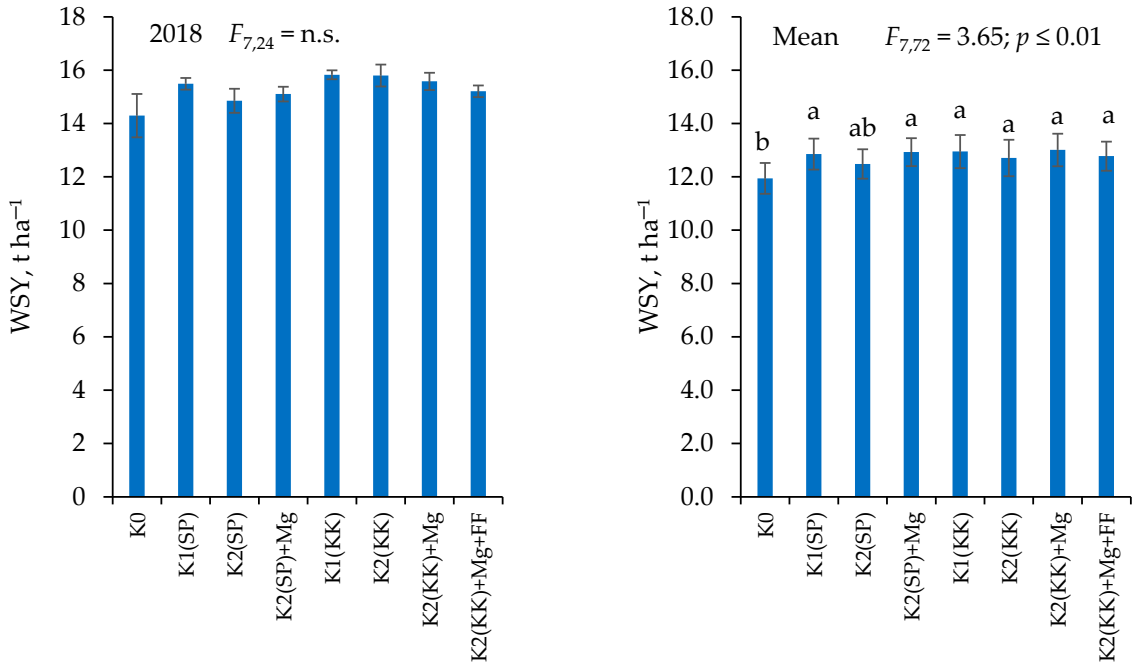

Figure 4. White sugar yield (WSY) in relation to the growing season and K fertilization treatment. Table 2 provides detailed information on fertilizers and their rates. Different letters indicate statistically significant differences between treatments (Tukey's HSD test; $p \leq 0.05$).

3.4. Relationships Between Yield and Quality Parameters

The correlation matrix between the independent variables, like BY and LY, and quality parameters and WSY is presented in Table 8.

Table 8. Correlation matrix—relationships between the yields of taproots and leaves and parameters of sugar beet quality assessment.

Variable	BY	LY	SC	K	Na	α-N
			Year 2016 (n = 8)			
LY	−0.30					
SC	0.02	−0.45				
K	0.28	0.03	−0.53			
Na	0.09	−0.18	−0.66	0.60		
α-N	−0.48	0.45	−0.08	0.09	−0.20	
WSY	0.96 ***	−0.43	0.27	0.10	−0.06	−0.58
			Year 2017 (n = 8)			
LY	0.11					
SC	−0.39	0.47				
K	0.66	−0.27	−0.47			
Na	0.44	−0.40	−0.82 *	0.52		
α-N	0.34	−0.27	−0.40	0.81 *	0.37	
WSY	0.95 ***	0.28	−0.10	0.53	0.19	0.19
			Year 2018 (n = 8)			
LY	0.39					
SC	−0.57	0.02				
K	−0.10	−0.30	−0.25			
Na	0.37	0.46	−0.20	−0.72 *		
α-N	−0.14	−0.73 *	0.02	0.67	−0.82 *	
WSY	0.96 ***	0.50	−0.35	−0.29	0.45	−0.26
			Years 2016–2018 (n = 24)			
LY	−0.31					
SC	0.65 **	0.15				
K	0.86 ***	−0.35	0.76 ***			
Na	0.87 ***	−0.50 *	0.55 *	0.86 ***		
α-N	0.58 **	0.13	0.93 ***	0.76 ***	0.49 *	
WSY	0.89 ***	−0.07	0.92 ***	0.89 ***	0.77 ***	0.84 ***

*, **, *** significance at $p \leq 0.05$, 0.01, 0.001, respectively. Key: BY—taproot yield; LY—leaf yield; SC—polarization, biological sucrose content; α-N—α-amino-N concentration; K and Na—potassium and sodium concentration.

WSY was significantly correlated with BY each year. Stepwise regression analysis indicates that this feature explains 91–93% of the variation in WSY (Equations (9), (11) and (13)). Including polarization (SC) in the regression Equations (10), (12) and (14) increased the prediction value to 99%:

$$2016: \text{WSY} = -0.633 + 0.176\ \text{TY};\ R^2 = 0.92;\ p \leq 0.001;\ n = 8 \quad (9)$$

$$\text{WSY} = -15.66 + 0.175\ \text{TY} + 0.802\ \text{SC};\ R^2 = 0.99;\ p \leq 0.001;\ n = 8 \quad (10)$$

$$2017: \text{WSY} = 1.513 + 0.129\ \text{TY};\ R^2 = 0.91;\ p \leq 0.001;\ n = 8 \quad (11)$$

$$\text{WSY} = -13.44 + 0.146\ \text{TY} + 0.813\ \text{SC};\ R^2 = 0.99;\ p \leq 0.001;\ n = 8 \quad (12)$$

$$2018: \text{WSY} = 2.410 + 0.155\ \text{TY};\ R^2 = 0.93;\ p \leq 0.001;\ n = 8 \quad (13)$$

$$\text{WSY} = -17.64 + 0.183\ \text{TY} + 0.852\ \text{SC};\ R^2 = 0.99;\ p \leq 0.001;\ n = 8 \quad (14)$$

The analysis of the relationships between the variables in the dataset, including the variability caused by the seasonal factor, indicates that the main parameter shaping WSY was sucrose content (polarization). Including another parameter, BY, increased the R^2 value to 0.99:

$$\text{Mean 2016–2017: WSY} = -7.32 + 1.066\ \text{SC};\ R^2 = 0.84;\ p \leq 0.001;\ n = 24 \quad (15)$$

$$\text{WSY} = -12.89 + 0.169\ \text{TY} + 0.679\ \text{SC};\ R^2 = 0.99;\ p \leq 0.001;\ n = 24 \quad (16)$$

It is worth noting that for the "year × fertilization" interaction data, there was a positive correlation between WSY and the content of molasses-forming compounds. However, only the LY level had no significant relationship with WSY (Table 7). The obtained correlation matrix again emphasizes the dominant role of the seasonal factor. This factor plays a key role in shaping BY and consequently WSY.

3.5. Nitrogen Use Efficiency

In the studies, the efficiency of N use was assessed using the following indices: partial factor productivity of N fertilizer (PFP_f), agronomic efficiency (AE), biomass productivity (NUE_s), and partial factor productivity of N from soil and fertilizers (PFP_{in}). The average values of these indices over the three years of the study were 689.1, 199.0, 515.5, and 346.2 kg kg^{-1}, respectively. The growing season was the main factor modifying the NUE indices (Table 9). The highest values of the PFP_f, AE, and PFP_{in} were obtained in 2018. Meanwhile, PFP_{in} values did not differ significantly between 2016 and 2017. The highest NUE_s index was obtained in 2016, and again in 2018. Fertilizer application significantly affected three indices: PFP_f, AE, and PFP_{in}. The highest mean values of these indices were obtained with the K_2 (KK) + Mg treatment. They were significantly higher than in the potassium control (K_0). Significant increases in the index values were also obtained with other treatments with K, except for one: K_2 (SP). Furthermore, applying magnesium sulfate to the soil slightly improved the PFP, AE, and PFP values compared to those obtained after applying potassium salt or Korn-Kali only. Unlike previous indices, fertilization did not significantly affect the NUE_s index. However, the lowest NUE_s value was obtained when K fertilization was omitted. Additionally, the highest NUE_s value was found with the K_1 (KK) treatment, followed by the K_2 (KK) + Mg + FF treatment. The values of the assessed NUE indices were also modified by seasonal factors. Supplementary Material provides detailed data on the effect of the fertilization factor on NUE indices in individual years (Table S5).

Table 9. Nitrogen use efficiency (NUE) indices in relation to the growing season and K fertilization treatment (mean ± SEM).

Year/Treatment	PFP_f kg kg^{-1}	AE kg kg^{-1}	NUE_s kg kg^{-1}	PFP_{in} kg kg^{-1}
Mean	689.1 ± 6.0	199.0 ± 7.4	515.5 ± 4.0	346.2 ± 2.6
2016	645.2 ± 7.4 ^{c}	138.5 ± 7.4 ^{c}	532.8 ± 5.9 ^{a}	337.8 ± 3.9 ^{b}
2017	669.0 ± 4.7 ^{b}	173.3 ± 4.7 ^{b}	482.0 ± 4.5 ^{b}	329.2 ± 2.3 ^{b}
2018	753.3 ± 6.4 ^{a}	285.3 ± 6.4 ^{a}	531.5 ± 6.3 ^{a}	371.6 ± 3.2 ^{a}
F ratio	127.4 ***	232.4 ***	29.2 *	75.9 ***
K_0	648.3 ± 15.0 ^{b}	158.2 ± 19.2 ^{b}	493.8 ± 9.1	325.7 ± 6.4 ^{b}
K_1 (SP)	702.3 ± 15.2 ^{a}	212.2 ± 19.7 ^{a}	525.0 ± 9.8	352.7 ± 5.9 ^{a}
K_2 (SP)	671.1 ± 12.7 ^{ab}	181.0 ± 17.1 ^{ab}	503.5 ± 7.7	337.2 ± 5.2 ^{ab}
K_2 (SP) + Mg	703.5 ± 14.5 ^{a}	213.4 ± 18.7 ^{a}	510.9 ± 10.3	353.5 ± 6.4 ^{a}
K_1 (KK)	700.5 ± 20.2 ^{a}	210.3 ± 24.9 ^{a}	529.0 ± 8.3	351.5 ± 7.9 ^{a}
K_2 (KK)	691.3 ± 22.4 ^{a}	201.2 ± 27.0 ^{a}	519.5 ± 16.1	347.1 ± 9.8 ^{a}
K_2 (KK) + Mg	707.4 ± 16.9 ^{a}	217.3 ± 20.7 ^{a}	516.2 ± 13.3	355.7 ± 8.4 ^{a}
K_2 (KK) + Mg + FF	688.9 ± 13.0 ^{a}	198.8 ± 14.2 ^{a}	525.7 ± 13.4	346.2 ± 5.7 ^{a}
F ratio	6.0 ***	6.0 ***	n.s	5.81 ***
		Year × Treatment Interaction		
F ratio	2.2 *	2.2 *	n.s	2.1 *

*, *** significance at $p \leq 0.05$, 0.001, respectively; n.s., not significant. Different letters indicate significant differences between treatments (Tukey's HSD test; $p \leq 0.05$). Key: PFP_f—partial factor productivity of N fertilizer; AE—agronomic efficiency; NUE_s—biomass productivity; PFP_{in}—partial factor productivity of N from soil and fertilizers.

4. Discussion

Over the last 10 years, the average sugar beet yield (BY) in Poland has ranged from 52.0 to 68.3 t ha^{-1}, depending on the year [1]. In the experiments conducted, the beet yield was higher. In 2016 and 2017, it was 71–73 t ha^{-1}, approximately 15% higher than the 10-year average. An even higher root yield of 82.9 t ha^{-1} was obtained in 2018, which was 33% higher than the 10-year average. The higher BY in the experiment was due to favorable weather conditions and relatively good soil fertility during the growing season. Total precipitation during the 2016–2018 growing seasons was lower than the recommended 550–750 mm. However, the distribution of precipitation during these seasons favored high yields [3]. In 2016, total precipitation in June and July met the basic requirement of 150 mm for high yields. Precipitation, especially in July (113 mm), was highly favorable for the rapid growth and yield of sugar beet plants. Furthermore, average temperatures of 18–19 °C favored plant development without generating losses in dry matter yield [2]. September precipitation was significantly lower than the long-term average (Figure 2). However, this did not affect LY, which stimulated sucrose accumulation in the taproots.

Weather conditions in 2017 were also favorable. April was colder than the long-term average, which delayed seed emergence. However, the temperature in June and July was highly advantageous for plant growth, which reached critical stages a few days earlier than the long-term average. The high precipitation in July and August (153 mm) was favorable for the rapid canopy growth. Unfortunately, hail on August 12th destroyed a significant portion of the sugar beet canopy, delaying plant growth by about one month. As a result, BY losses were estimated at 15 t ha^{-1}. The lowest LY was also obtained this year. Additionally, the plants regrew foliage by mid-September and experienced rapid growth in October. Consequently, the taproots had the lowest content of biological sugar (SC) and α-N. Consequently, the lowest sugar losses to molasses (SML values) were recorded this year.

The growing conditions for sugar beets in the 2018 vegetative season may be considered to have been poor. Despite this, the highest BY was achieved this year. The average monthly temperatures since the start of the growing season were 2–3 °C above the long-term averages. Furthermore, the soil was well moistened after winter, and the increased precipitation in July (106 mm) resulted in the vigorous growth of sugar beet plants, even during the extremely dry month of August. Preliminary symptoms of water deficiency were observed at the end of September. At that time, the first symptoms of a

strong *Cercospora beticola* attack were revealed, which led to the full destruction of the sugar beet canopy within one month. By harvest time, 80% of the leaves were dead, resulting in low biomass of tops (LY). This resulted in a significantly lower BY/LY ratio compared to in 2016–2017.

The high sugar beet yield in 2018 was supported by the high concentrations of plant-available K, Mg, and Ca in the deeper soil layers. Under non-limiting conditions, sugar beets can grow roots up to one meter deep and extract water and nutrients from that depth [41]. Soils in Poland are naturally deficient in cations, particularly Ca [42]. In soils that are naturally low in Ca, sugar beets respond to the application of Ca, even at low rates [43]. Calcium is an important component of the soil exchangeable complex (CEC) and a plant nutrient. It is essential for maintaining proper soil pH and promoting the formation of soil micro-aggregates. These micro-aggregates affect root growth conditions in the soil, including subsoil conditions [44]. As a plant macronutrient, Ca is essential for root bud formation and root system development [45]. Calcium is also important for a plant's tolerance of abiotic stress caused by factors such as water deficiency and excessive temperatures [46,47].

The effect of balanced K fertilization on beet yield and quality was smaller compared to weather factors. However, a positive effect of K fertilization on BY was obtained regardless of the fertilizer's rate or chemical composition. The average BY increased by 6.5% to 7.9% in all K-treated treatments, depending on the year of the study. The lowest BY increase occurred in 2017, while the highest increase occurred in 2018. This small difference was likely caused by compensating responses to the two main factors that form beet yield: low K and Ca content in the soil in the first year and unfavorable weather conditions in the second year. Sugar beets respond very well to K fertilization in soils that are poor in this macronutrient [14,48]. However, a shortage of plant-available Ca in the soil, particularly in the deeper layers, limits the positive response of sugar beets to K fertilization [49]. Calcium plays a crucial role in maintaining the appropriate cation balance in plant tissues [45]. In 2018; moreover, when the plants were heavily infected with *Cercospora beticola*, K fertilization increased LY. This result can also be explained by the positive role of K in the plant response to biotic stress [50].

K plays a significant role in the uptake of N in the form of NO_3^- due to N's important role in shaping the growth rate, yield, and quality of sugar beets [16]. A lack of K in the growth environment of beets until the rows are closed causes slower growth, which extends the period of forming an effective assimilation surface. This leads to decreased taproot and final sugar yield [32]. Several authors have observed increased sugar beet yields and improved taproot quality related to sucrose content as a result of K fertilization [7,19,51–53]. In our studies, no significant effect of fertilization on SC was found in any year. This result could be due to the stimulation of plant growth by K (and other nutrients), which leads to the dilution of SC in taproots. One negative effect of applying K to the soil is an increase in its concentration in taproots, which in turn causes problems with sugar production [39,48]. However, this study did not reveal significant differences in K content between the control and K-treated plants. Only a slight increase in K concentration was observed in the treatment with the highest rate of potassium salt [K_2 (PS)], and lower BY compared to K_1 (PS) treatment. Potassium fertilization is also associated with the possibility of disrupting the uptake of other cations (e.g., Mg^{2+}, Ca^{2+}, and Na^+) due to competition for binding sites in the apoplast and cell membrane transporters [54]. This phenomenon could explain the reduced BY trend in the treatment with the highest K rate in the form of potassium salt [K_2 (PS)] without the simultaneous application of other cations. This trend was observed in each year of the study. Consequently, the optimal potassium salt

rate under these experimental conditions, even in soil with low plant-available K content, is assumed to be 83 kg K ha^{-1} (K_1 treatment).

The yield-enhancing effect of K fertilization can be increased by the simultaneous application of other nutrients (Mg, S) in balanced amounts [55]. Thanks to this, in this study, the sugar beet yield was high after the application of 160 kg K ha^{-1} (treatment K_2). However, this effect was significantly modified by weather conditions and soil properties. Consequently, a specific trend in the plants' response to the applied fertilization was evident in each growing season. In 2016, the highest BY value was obtained by applying a K_2 rate and additional Kieserite fertilization. This result was unrelated to whether the beets were fertilized with potassium salt or Korn-Kali. Compared to the K_1 rate treatment, the difference ranged from 3.1% to 11.1%. This positive response to Mg can be attributed primarily to the low concentration of this nutrient in the soil that year. This relationship confirms the results of previous studies [27,56]. For example, Pogłodziński et al. [57] found that magnesium sulfate fertilization at 24 kg Mg ha^{-1} increased BY by 3.7–7.4% compared to the control without Mg application, with the reaction depending on the N rate. Additionally, the application of magnesium sulfate improves the nutritional status of plants with S [31]. Mg and S fertilization has a positive effect on BY and improves crop quality by stimulating sucrose accumulation and reducing α-N concentration in taproots [29]. However, no significant effect of Mg and S on taproot quality was found in this study. Other authors have also pointed out the lack of a significant effect of Mg soil application on the quality of sugar beet [55].

In 2017, the soil also had low levels of plant-available K, and plants responded positively to K fertilization, especially to potassium sulfate at a K1 dose. However, additional Mg and S fertilization did not increase the yield. This can be explained by the higher level of plant-available Mg in the soil in 2017 compared to 2016. Furthermore, the soil's Ca content was exceptionally low, even in the deeper layers. Unlike in previous years, there was little difference in the effect of the type of potassium fertilizer in 2018. Higher yields were obtained with Korn-Kali than with KCl. This can be explained by the presence of K, Mg, S, and sodium (Na) in Korn-Kali. Sugar beets are natrophilic plants that respond positively to Na applications [58]. Sodium has a beneficial effect on water balance, leaf surface, and thickness due to the increased rate of cell expansion and the number and activity of stomata in sugar beet [59]. In general, Na application should result in the highest BY efficiency in soils with low levels of available K. Under these conditions, a simple K substitution mechanism with Na takes place [60]. However, even in soils with sufficient K content, beets respond positively to Na, especially in dry years [14]. Sodium plays a role in regulating ionic homeostasis (e.g., K/Na, K/Mg) and related nitrogen metabolism [10].

Compared to other crops, sugar beet has a high nitrogen use efficiency (NUE), particularly from soil sources. In The Netherlands, for example, the average NUE—calculated as the ratio of nitrogen inflow to outflow from the soil–plant system—reached 0.95 kg N kg^{-1} N [61]. Nevertheless, improving NUE remains a primary goal of modern sugar beet cultivation. This goal can be achieved through variety improvement and the use of appropriate agrotechnologies, such as N fertilization [8,62]. In general, as the N dose increases, various NUE indicators decrease [44,63]. However, within a given N dose, NUE indicators (e.g., PFP_f and AE) can be improved by maintaining an appropriate N balance. Barłóg et al. [64] obtained PFP_f values ranging from 493 to 964 kg BY kg N^{-1}. According to these authors, the highest PFP_f values can be obtained through localized N application and with P and K doses that are 50% lower than the recommended amount. In our study, mean PFP_f values within the variability range induced by fertilization alone ranged from 648 to 707 kg BY kg N^{-1}. The lowest PFP_f, EA, and NUE_s values were obtained in the control without K, confirming that K deficiency negatively affects N utilization [7]. The increase in

NUE_s index values results directly from potassium's yield-forming functions in sugar beet plants. However, excess K reduces NUE_s values due to disruptions in plant maturation and leaf growth at the expense of taproot biomass [65]. There were no significant differences between K_1 and K_2 levels, but they were consistent year after year. As demonstrated in this study, however, additional Mg and S fertilization improves NUE_s and minimizes the adverse effects of using higher rates of K alone. This finding aligns with prior research indicating that both nutrients facilitate the efficient use of N rates [57].

This study found that the additional application of Mg and S via foliar spray did not improve BY, quality, or NUE. Although the foliar spray significantly reduced the amount of α-N compared to the control and thus increased the white sugar content (WSC) in taproots, this did not significantly impact the final sugar beet crop product (WSY), as the BY increases were lower than in other K treatments. In each year of the study, BY was a significant variable influencing WSY. The role of SC as the dominant variable was revealed by the dataset covering all observations from the three years. However, this relationship primarily resulted from the interaction of climatic and soil factors affecting sugar beet yield and quality. In this regard, the correlation between SC and K content in taproots should be emphasized. This correlation resulted from the varying plant-available K content in the soil and the distinct weather patterns during the growing seasons.

5. Conclusions

The response of sugar beets to various types of potassium fertilizers and magnesium sulfate depends on weather conditions and the soil's content of plant-available cations (K, Mg, and Ca). The simultaneous soil application of potassium and magnesium sulfate produced the best results in years when the soil concentrations of plant-available K and Mg were low. Conversely, the combined application of K, Mg, S, and Na (in the form of Korn-Kali) had the greatest effect on taproot and white sugar yield (WSY) in years with unfavorable weather conditions and in soils with high concentrations of plant-available Ca in deeper layers. Unlike beet yield, mineral fertilization had no significant effect on most taproot quality parameters, regardless of the K rate or additional magnesium sulfate fertilization (including foliar application). The exception was α-N concentration, which decreased significantly with K application. The experiments clearly demonstrated the positive effects of potassium fertilization on nitrogen use efficiency (NUE) indicators, particularly when magnesium sulfate was applied to the soil simultaneously. Therefore, balancing N and K, along with other nutrients such as Mg and S, is key to boosting sugar beet yield, especially in naturally cation-poor soils, such as in this area. Balanced fertilization allows us to reduce the rate of N and obtain high-quality raw material for sugar production. However, determining the correct dose and type of fertilizers containing K, Mg, S, and Na requires determining the soil's potential to supply plants with the abovementioned nutrients, as well as calcium.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agronomy15092075/s1, Table S1: Two-way ANOVA results: effect of growing season (year) and fertilization treatment on the sugar beet yield (BY), leaf yield (LY) and BY/LY ratio; Table S2: Taproot yield-to-leaf weight (BY/LY) ratios in relation to the growing season and potassium (K) fertilization treatment (mean ± SEM); Table S3: The quality parameters of sugar beet taproots in relation to the growing season and K fertilization treatment (mean ± SEM); Table S4: Two-way ANOVA results: effect of growing season (year) and fertilization treatment on the white sugar yield (WSY); Table S5: Nitrogen use efficiency (NUE) indices in relation to the growing season and K fertilization treatment (mean ± SEM).

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